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New Strategies to Extract CKM Phases from Non-Leptonic B Decays

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New strategies to extract CKM phases from non-leptonic B decays

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Several new strategies to extract CKM phases, including a determination of γ from $B_{s(d)} \to J/\psi\, K_{\rm S}$ decays and a general approach, which makes use of the angular distributions of certain $B_{d,s}$ modes, such as $B_d \to J/\psi\, \rho^0$ and $B_s \to J/\psi\, \phi$, are discussed. Special emphasis is put on a simultaneous determination of β and γ with the help of the decays $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$, which relies only on the U-spin flavour symmetry of strong interactions and is not affected by any penguin or final-state-interaction effects.

1. Introduction

Among the central targets of future B-physics experiments is the direct measurement of the three angles α, β and γ of the unitarity triangle of the Cabibbo–Kobayashi–Maskawa (CKM) matrix. However, only the extraction of β with the help of the "gold-plated" mode $B_d \to J/\psi K_{\rm S}$ is quite straightforward. In the test of the Standard-Model description of CP violation, the determination of the angle γ is a crucial element. Since the e^+e^- B-factories operating at the $\Upsilon(4S)$ resonance will not be in a position to explore B_s decays, a strong emphasis was given so far, in the literature, to decays of non-strange B-mesons. However, also the B_s system provides interesting strategies to determine γ, which appear promising for dedicated B-physics experiments at hadron machines, such as LHCb (CERN) or BTeV (Fermilab). The new strategies, discussed here, are—in contrast to clean strategies using pure "tree" decays, such as $B_s \to D_s^\pm K^\mp$—very sensitive to new-physics contributions to the corresponding decay amplitudes and may play an important role to explore the physics beyond the Standard Model.

2. Extracting γ from $B_{s(d)} \to J/\psi\, K_{\rm S}$

The decays $B_s \to J/\psi\, K_{\rm S}$ and $B_d \to J/\psi\, K_{\rm S}$ are related to each other by interchanging all down and strange quarks, i.e. through the U-spin flavour symmetry of strong interactions. Whereas the CP-violating weak phase factor $e^{i\gamma}$ is strongly Cabibbo-suppressed in the decay amplitude of the "gold-plated" mode $B_d \to J/\psi\, K_{\rm S}$, this is not the case in $B_s \to J/\psi\, K_{\rm S}$. Consequently, there may be sizeable CP-violating effects in this channel, which are due to certain penguin topologies. If we make use of the U-spin flavour symmetry, the CKM angle γ and interesting hadronic quantities can be extracted by combining the "direct" and "mixing-induced" CP asymmetries $\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to J/\psi\, K_{\rm S})$ and $\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to J/\psi\, K_{\rm S})$ with the CP-averaged $B_{d(s)} \to J/\psi\, K_{\rm S}$ branching ratios [1]. Remarkably, the theoretical accuracy of this approach is only limited by U-spin-breaking corrections. In particular, there are no problems due to final-state-interaction (FSI) effects. An interesting by-product of this strategy is that it allows us to take into account the—presumably very small—penguin contributions in the determination of the B_d^0–$\overline{B_d^0}$ mixing phase $\phi_d = 2\beta$ from $B_d \to J/\psi\, K_{\rm S}$, which is an important issue in view of the impressive accuracy that can be achieved with second-generation B-physics experiments. Moreover, we have an interesting relation between the direct $B_{s(d)} \to J/\psi\, K_{\rm S}$ CP asymmetries and the corresponding CP-averaged branching ratios:

$$\frac{\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to J/\psi\, K_{\rm S})}{\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to J/\psi\, K_{\rm S})} \approx -\frac{{\rm BR}(B_s \to J/\psi\, K_{\rm S})}{{\rm BR}(B_d \to J/\psi\, K_{\rm S})}\,. \tag{1}$$

The experimental feasibility of the extraction of γ sketched above depends strongly on the size of the penguin effects in $B_s \to J/\psi\, K_{\rm S}$, which are very hard to estimate. A similar strategy is provided by $B_{d(s)} \to D^+_{d(s)}\, D^-_{d(s)}$ decays. For a detailed discussion, the reader is referred to [1].

3. Extracting β and γ from the decays $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$

In the literature, $B_d \to \pi^+\pi^-$ usually appears as a tool to probe $\alpha = 180^\circ - \beta - \gamma$. However, penguin contributions preclude a reliable determination of α from the CP-violating observables of the decay $B_d \to \pi^+\pi^-$ that arise in the usual time-dependent CP asymmetry

$$a_{\rm CP}(t) = \mathcal{A}_{\rm CP}^{\rm dir}\cos(\Delta M_d t) + \mathcal{A}_{\rm CP}^{\rm mix}\sin(\Delta M_d t). \quad (2)$$

Although several strategies were proposed to control these penguin uncertainties, they are usually very challenging from an experimental point of view.

In the following, a new way of using the CP-violating observables of $B_d \to \pi^+\pi^-$ is discussed [2]: combining them with those of $B_s \to K^+K^-$—the U-spin counterpart of $B_d \to \pi^+\pi^-$—a simultaneous determination of $\phi_d = 2\beta$ and γ becomes possible. This approach is not affected by any penguin topologies—it rather makes use of them—and does not rely on certain "plausible" dynamical or model-dependent assumptions. Moreover, FSI effects, which attracted considerable attention in the recent literature in the context of the determination of γ from $B \to \pi K$ decays, do not lead to any problems, and the theoretical accuracy is only limited by U-spin-breaking effects. This strategy, which is also very promising to search for indications of new physics [3], is conceptually quite similar to the extraction of γ from $B_{s(d)} \to J/\psi\, K_{\rm S}$ discussed in the previous subsection. However, it appears to be more favourable in view of the U-spin-breaking effects and the experimental feasibility.

If we make use of the unitarity of the CKM matrix and apply the Wolfenstein parametrization, generalized to include non-leading terms in $\lambda \equiv |V_{us}| = 0.22$, the $B_d^0 \to \pi^+\pi^-$ decay amplitude can be expressed as follows [2]:

$$A(B_d^0 \to \pi^+\pi^-) = e^{i\gamma}\left(1 - \frac{\lambda^2}{2}\right)\mathcal{C}\left[1 - d\,e^{i\theta}e^{-i\gamma}\right], \quad (3)$$

where

$$\mathcal{C} \equiv \lambda^3 A\, R_b\left(A_{\rm cc}^u + A_{\rm pen}^{ut}\right), \quad (4)$$

with $A_{\rm pen}^{ut} \equiv A_{\rm pen}^u - A_{\rm pen}^t$, and

$$d\,e^{i\theta} \equiv \frac{1}{(1-\lambda^2/2)R_b}\left(\frac{A_{\rm pen}^{ct}}{A_{\rm cc}^u + A_{\rm pen}^{ut}}\right). \quad (5)$$

Here $A_{\rm cc}^u$ is due to current–current contributions, whereas the amplitudes $A_{\rm pen}^j$ describe penguin topologies with internal j quarks ($j \in \{u, c, t\}$). The relevant CKM factors are given by $A \equiv |V_{cb}|/\lambda^2$ and $R_b \equiv |V_{ub}/(\lambda V_{cb})|$. In analogy to (3), the $B_s^0 \to K^+K^-$ decay amplitude can be parametrized as

$$A(B_s^0 \to K^+K^-) = e^{i\gamma}\lambda\,\mathcal{C}'\left[1 + \frac{1}{\varepsilon}\,d'e^{i\theta'}e^{-i\gamma}\right], \quad (6)$$

where

$$\mathcal{C}' \equiv \lambda^3 A\, R_b\left(A_{\rm cc}^{u'} + A_{\rm pen}^{ut'}\right) \quad (7)$$

and

$$d'e^{i\theta'} \equiv \frac{1}{(1-\lambda^2/2)R_b}\left(\frac{A_{\rm pen}^{ct'}}{A_{\rm cc}^{u'} + A_{\rm pen}^{ut'}}\right) \quad (8)$$

correspond to (4) and (5), respectively, and $\varepsilon \equiv \lambda^2/(1-\lambda^2)$.

The decays $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ are related to each other by interchanging all down and strange quarks. Consequently, the U-spin flavour symmetry of strong interactions implies

$$d' = d \quad \text{and} \quad \theta' = \theta. \quad (9)$$

If we assume that the B_s^0–$\overline{B_s^0}$ mixing phase ϕ_s is negligibly small, as expected in the Standard Model, or that it is fixed through $B_s \to J/\psi\,\phi$ (see, for example, [4]), the four CP-violating observables provided by $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ depend—in the strict U-spin limit—on the four "unknowns" d, θ, $\phi_d = 2\beta$ and γ. We therefore have sufficient observables at our disposal to extract these quantities simultaneously. In order to determine γ, it suffices to consider $\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^+K^-)$ and the direct CP asymmetries $\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to K^+K^-)$, $\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^+\pi^-)$. If we make use, in addition, of $\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^+\pi^-)$, ϕ_d can be determined as well. The formulae to implement this approach in a mathematical way are given in [2].

If we use the B_d^0–$\overline{B_d^0}$ mixing phase as an input, there is a different way of combining $\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^+\pi^-)$, $\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^+\pi^-)$ with $\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to K^+K^-)$, $\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^+K^-)$. The point is that these observables allow us to fix contours in the γ–d and γ–d' planes as functions of the B_d^0–$\overline{B_d^0}$ and B_s^0–$\overline{B_s^0}$ mixing phases in a *theoretically clean* way. In order to extract γ and the hadronic parameters d, θ, θ' with the help of these contours, the U-spin relation $d' = d$ is sufficient. An illustration of this approach for a specific example can be found in [2]. A first experimental feasibility study for LHCb, using the same set of observables, gave an uncertainty of $\Delta\gamma|_{\rm exp} = 2.3^\circ$ for five years of data taking and looks very promising [5].

It should be emphasized that the theoretical accuracy of γ and of the hadronic parameters d, θ

and θ' is only limited by U-spin-breaking effects. In particular, it is not affected by any FSI or penguin effects. A first consistency check is provided by $\theta = \theta'$. Moreover, we may determine the normalization factors $\mathcal{C}$ and $\mathcal{C}'$ of the $B_d^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decay amplitudes (see (3) and (6)) with the help of the corresponding CP-averaged branching ratios. Comparing them with the "factorized" result

$$\left|\frac{\mathcal{C}'}{\mathcal{C}}\right|_{\rm fact} = \frac{f_K}{f_\pi}\frac{F_{B_sK}(M_K^2;0^+)}{F_{B_d\pi}(M_\pi^2;0^+)}\left(\frac{M_{B_s}^2 - M_K^2}{M_{B_d}^2 - M_\pi^2}\right), \tag{10}$$

we have another interesting probe for U-spin-breaking effects. Interestingly, the relation $d' e^{i\theta'} = d\, e^{i\theta}$ is not affected by U-spin-breaking corrections within a modernized version of the "Bander–Silverman–Soni mechanism", making use—among other things—of "factorization" to estimate the relevant hadronic matrix elements [2]. Although this approach appears to be rather simplified and may be affected by non-factorizable effects, it strengthens our confidence in the U-spin relations used for the extraction of β and γ from $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$.

The strategy discussed in this section is very promising for second-generation B-physics experiments at hadron machines, where the physics potential of the B_s system can be fully exploited. At the asymmetric e^+e^- B-factories operating at the $\Upsilon(4S)$ resonance, BaBar and BELLE, which have already seen the first events, this is unfortunately not possible. However, there is also a variant of the extraction of γ, where $B_d \to \pi^\mp K^\pm$ is used instead of $B_s \to K^+K^-$ [2]. This approach has the advantage that all required time-dependent measurements can in principle be performed at the asymmetric e^+e^- machines. On the other hand, it relies—in addition to the $SU(3)$ flavour symmetry—on the smallness of certain "exchange" and "penguin annihilation" topologies, which may be enhanced by FSI effects. Consequently, its theoretical accuracy cannot compete with the "second-generation" $B_d \to \pi^+\pi^-$, $B_s \to K^+K^-$ approach, which is not affected by such problems.

4. CKM phases and hadronic parameters from angular distributions of $B_{d,s}$ decays

An interesting laboratory to explore CP violation and the hadronization dynamics of non-leptonic B decays is provided by certain quasi-two-body modes $B_q \to X_1\, X_2$ of neutral $B_{d,s}$-mesons, where both X_1 and X_2 carry spin and continue to decay through CP-conserving interactions. In a recent paper [6], the general formalism to extract CKM phases and hadronic parameters from the corresponding observables, taking also into account penguin contributions, was presented. If we fix the mixing phase ϕ_q separately, it is possible to determine a CP-violating weak phase ω, which is usually given by the angles of the unitarity triangle, and interesting hadronic quantities as a function of a *single* hadronic parameter. If we determine this parameter, for instance, by comparing $B_q \to X_1\, X_2$ with an $SU(3)$-related mode, all remaining parameters, including ω, can be extracted. If we are willing to make more extensive use of flavour-symmetry arguments, it is possible to determine the B_q^0–$\overline{B_q^0}$ mixing phase ϕ_q as well.

A particularly interesting application of this approach is given by $B_d \to J/\psi\, \rho^0$, which can be combined with $B_s \to J/\psi\, \phi$ to extract the B_d^0–$\overline{B_d^0}$ mixing phase and—if penguin effects in the former mode should be sizeable—also the angle γ of the unitarity triangle. As an interesting by-product, this strategy allows us to take into account the penguin effects in the extraction of the B_s^0–$\overline{B_s^0}$ mixing phase from $B_s \to J/\psi\, \phi$. Moreover, a discrete ambiguity in the extraction of the CKM angle β can be resolved, and valuable insights into $SU(3)$-breaking effects can be obtained.

Other applications of the general formalism presented in [6] involve $B_d \to \rho\rho$ and $B_{s,d} \to K^*\overline{K^*}$ decays. Since this approach is very general, it can be applied to many other decays. Detailed studies are required to explore which channels are most promising from an experimental point of view.

5. Conclusions

The new strategies discussed above provide an exciting playground for second-generation B-decay experiments, such as LHCb or BTeV.

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